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Catchability and sampling of three species of juvenile penaeid prawns in the Embley River, Gulf of Carpentaria, Australia

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ABSTRACT: Tidal, diurnal, lunar and seasonal cycles of catchability of juvenile *Penaeus merguiensis*, *P. esculentus* and *Metapenaeus endeavouri* were investigated in the Embley River in the Gulf of Carpentaria, Australia, over a full year. After seasonal effects were removed, catches of all species were found to be influenced by day-night and tidal cycles. *P. merguiensis* catches were primarily influenced by the tidal cycle and secondarily by the day-night cycle. The largest catches were usually on the last stage of the ebb tide which had the greater range of the 2 daily tides. When the 2 ebb tides were of equal amplitude more prawns were caught during the night tide. Catches of *M. endeavouri* were most strongly influenced by the day-night cycle; virtually no prawns were caught during the day. *P. esculentus* catches were least influenced by the tide and day-night cycles although, in general, more were caught at night and towards low tide. Tide and light cycles appear to affect the basic activity patterns of each of the 3 species in a similar manner, although the relative strengths of the responses are different for each species. All species were more active near high tide and catches were lowest at this time. Towards low tide, activity decreased and catches increased. However, when water levels were very low, *P. esculentus* and *M. endeavouri* buried in the substrate and, therefore, were not catchable by trawling. In contrast, *P. merguiensis* did not bury, but concentrated near the shallow water's edge at low tide, and catches were highest then. All species were more active at night than during the day and catches were higher at night. The relationship between activity and catchability was different for the day-night and tidal cycles. Catchability with respect to day-night increased when the prawns were more active but catchability with respect to tide increased when the prawns were less active. The results of the study are applicable to many areas in Australia and the Indo-West Pacific where similar habitats are used by juvenile penaeid prawns.

INTRODUCTION

Sampling of juvenile prawns is complicated by the extreme variability in catch rates of trawl gear in time and space. Two approaches to overcoming variability in time have been considered. The first attempts to standardize sampling by using gear that is not susceptible to the changes in catchability of the prawns over short periods of time. Examples of this approach are the use of jet nets to flush prawns from sandy substrates (Penn & Stalker 1975) and drop traps that capture all enclosed prawns, whether buried or not (Zimmerman et al. 1984). The second approach uses sampling gear that is affected by short-term changes in the availability and catchability of prawns but standardizes sampling by limiting it to the period of highest catch rate each day. This was used successfully by Staples & Vance (1979) for *Penaeus merguiensis* in the Norman River, southern Gulf of Carpentaria, Australia, after a detailed study of the periodicity of catchability. Before adopting this approach, however, the patterns of variability of the different species at a study site must be fully documented.

Variability in the catches of juvenile penaeids has been described in response to day-night cycles (e.g. Trent 1966, Young 1975, Coles 1979) and tidal cycles (e.g. Staples & Vance 1979). Laboratory studies have shown changes in prawn activity associated with day-night (e.g. Hindley 1975, Subrahmanyan 1976, Reynolds & Casterlin 1979), tidal cycles (e.g. Hughes 1972), moonlight (Fuss & Ogren 1966), turbidity (Minello et al. 1987), temperature (Aldrich et al. 1968) and salinity (e.g. Lakshmi et al. 1976).

To assess the short-term variability in catchability of juveniles of the main commercial penaeids in the Gulf of Carpentaria, a 1 yr study was carried out in the

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Embley River estuary near Weipa in the northeastern Gulf. This study site contains a wide variety of habitats that are nursery areas for the juveniles of the 5 commercial species caught in the immediate offshore waters (Staples et al. 1985). Several of the prawn species caught in this area are of commercial importance throughout the Indo-West Pacific region and the estuarine habitats studied here are also utilized by juvenile penaeids throughout the region. This paper documents the tidal, diurnal and seasonal variation in the catch of *Penaeus merguiensis*, *P. esculentus* and *Metapenaeus endeavouri* and seeks to identify the environmental factors responsible for the variation.

METHODS

We used the same data set that Staples et al. (1985) used for describing the habitat preferences of juvenile *Penaeus merguiensis*, *P. esculentus* and *Metapenaeus endeavouri* in the Embley River, Gulf of Carpentaria, but have used only the data from the habitat types where the 3 species were most abundant. These were: a steeply sloping intertidal mudbank lined with mangroves for *P. merguiensis*; and an intertidal seagrass flat for *P. esculentus* and *M. endeavouri* (Fig. 1).

Each site was sampled every 2 h for 24 h every 3 wk at the peak of alternate spring and neap tides between August 1981 and August 1982. Trawls were made along a fixed 200 m transect using a 2 mm mesh net with a 1 mm cod-end fixed to a 1 × 0.5 m rectangular beam trawl. On the steeply sloping mudbank site, trawls were made parallel to the bank, usually within 3 m of the water's edge, and in less than 0.5 m of water. On all spring high tides and some neap high tides, water entered the mangroves; at these times trawls were made about 2 m from the edge of the mangroves. On the seagrass flat, trawls were made perpendicular to the bank except on most spring low tides and some neap low tides when the seagrass was exposed. At these times a trawl was made as close as possible to the seagrass beds, parallel to the bank.

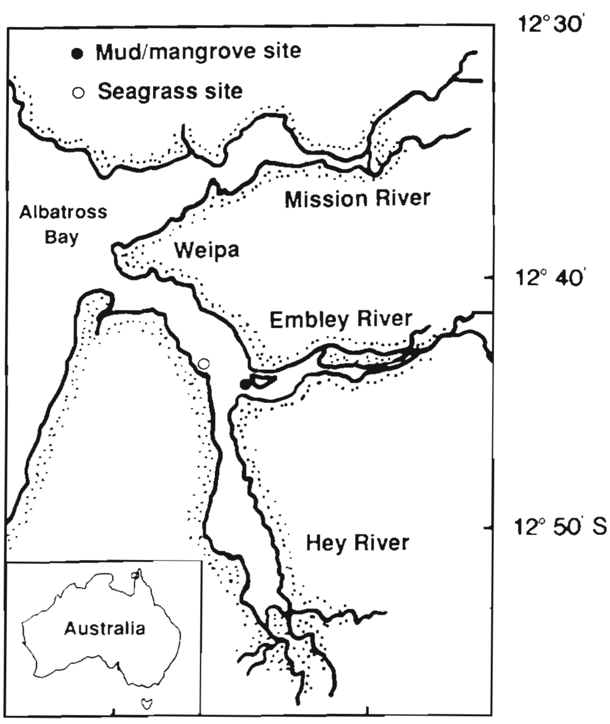

Fig. 1. Albatross Bay and Embley River study area in the northeastern Gulf of Carpentaria showing sampling sites

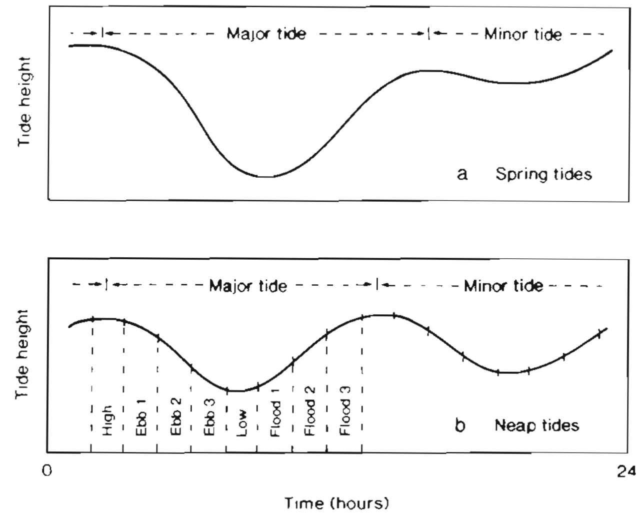

Fig. 2. Generalized (a) spring and (b) neap tidal cycles with definitions of tide ranges and tide stages used in the analysis. See text for explanation

All penaeid prawns were identified to species, and the carapace lengths (CL) measured to the nearest millimetre using either vernier calipers or an ocular micrometer. *Penaeus merguiensis* data were divided into 2 size groups: benthic postlarvae (1 to 2.9 mm CL) and juveniles (>2.9 mm CL). Postlarvae of the other 2 species could not be identified reliably so were not included in the analyses.

The main environmental changes in an estuary in 24 h are related to the tidal and the day-night cycle. Tides in the Embley estuary are mainly semidiurnal and the pattern of daily tide height variation changes throughout the fortnightly spring-neap tidal cycle (Fig. 2). Between August 1981 and August 1982, the daily tide range varied from 2.4 m on the largest spring tide to 0.7 m on the smallest neap tide. On neap tides, the 2 daily tides are of roughly equal amplitude, whereas on spring tides there is 1 major tide of large range and 1 minor tide of smaller range and often of shorter duration. For statistical analyses the duration of the tide types was defined from high tide to high tide, with the major tide being the one with the greater range (Fig. 2a). Each tide type was divided into 8 stages: high, low and 3 each of ebb and flood tide stages (Fig. 2b). For each trawl, water temperature, salinity and depth were measured and cloud cover was estimated. Expected moonlight intensity for each trawl was calculated following Austin et al. (1976). Predicted hourly tide heights for Weipa were supplied by the CSIRO Division of Oceanography (J. A. Church pers. comm.).

Statistical analyses were done with the General Linear Models procedure of the SAS statistical package (SAS Institute Inc. 1988). Comparing the diel and tidal patterns of catch variation between weeks was complicated by the large seasonal variation in catches, which tended to mask the short-term variability. The variability of beam trawl catches was therefore analysed using analysis of variance: the data were treated as a split plot experiment to accommodate the different temporal scales inherent in the sampling design. This allowed the removal of long-term variation (week to week) before examining short-term variation (diel and tidal). Three levels of time scale and therefore error variation were used:

Level 1: variability between sampling weeks;
Level 2: variability between tide types on the same day;
Level 3: variability between stages of the same tide type.

The error estimates for each level were: (1) week; (2) interaction of week and tide type; and (3) interaction of week, tide type and tide stage, respectively. The variables tested in the analysis at each level (Table 1) were those that showed some variation over the time scale for that level. Because the catch data contained large numbers of zeros, catches were transformed as $\log_{10}(\text{catch} + 0.1)$ to satisfy the assumptions of normality. The effect of season was tested by regressing catch against unimodal sine and cosine curves with a period of 12 mo and bimodal sine and cosine curves with a period of 6 mo.

Table 1. Details of the split-plot analysis of variance used for each species including the time scale used at each level, the grouping variable used to define each level and the variables used in the analysis at each level

Level	Time scale	Grouping variable	Analysis variable
1	Weeks	Week	Unimodal season Bimodal season Tide phase Moon phase Mean sea level Salinity Temperature Interactions
2	Day	Tide type	Tide type Day-night Salinity Temperature Interactions
3	Hours	Tide stage	Tide stage Tide height Depth Day-night Moonlight Salinity Temperature Interactions

RESULTS

Penaeus merguiensis

Seasonal variation

Catches of juvenile *Penaeus merguiensis* varied substantially throughout the year and the variance on individual sampling dates was high. Mean catches were low from August through early December (Fig. 3). They increased sharply at the end of December and remained high until late April, after which they declined (Fig 3). In the analysis of variance the only significant variable at this level was a unimodal season variable that explained 13.5 % of total juvenile catch variation and 65.1 % of the variation at the weeks level (Table 2, Level 1).

Mean catches on most spring tides were higher than on neap tides, except from August to November when only 1 to 2 prawns were caught per 200 m trawl and comparisons were not meaningful (Fig. 3). Tidal phase explained a further 5.7 % of the variation at this level

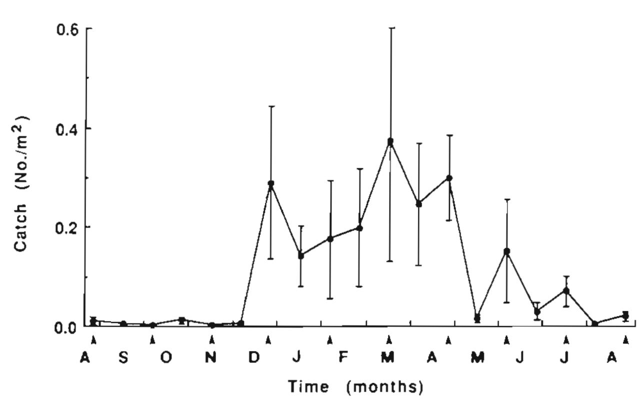

Fig. 3. Juvenile *Penaeus merguiensis*. Mean catches ± SE for each sampling period from August 1981 to August 1982. Arrowheads: dates of alternate spring tides. n = 13 for each point

Table 2. *Penaeus merguiensis*. Split-plot analysis of variance of log-transformed catches of juveniles with season, tide type, tide stage, tide height and day-night. Level 1 tests variability between weeks, Level 2 between tide types and Level 3 between tide stages. df: degrees of freedom; SS: sums of squares; % level variation: percentage of the catch variation explained by each variable at that level; and % total variation: percentage of the total catch variation explained by each variable. Only significant effects are included in the model

Split plot	Source of variation	df	SS	*F*-ratio	% Level variation	% Total variation
Level 1	Unimodal season	2	2.800	14.89***	65.1	13.5
(Weeks)	Error	16	1.506			
Level 2	Tide type	1	0.720	15.32***	34.5	3.5
(Day)	Day-night	1	0.219	4.66*	10.5	1.1
	Day-night × Unimodal season	2	0.399	4.26*	19.1	1.9
	Error	16	0.751			
Level 3	Tide stage	7	3.753	15.75***	29.6	18.1
(Hours)	Tide height	1	1.144	33.60***	9.0	5.5
	Day-night	1	0.391	11.48***	3.1	1.9
	Tide height × Tide stage	7	1.255	5.27***	9.9	6.0
	Tide stage × Unimodal season	14	1.138	2.38**	9.0	2.6
	Error	132	4.493			

*0.01 < p < 0.05, **0.001 < p <0.01, ***p < 0.001

but was not significant in the analysis ($0.05 < p < 0.10$). When data from the last half of the year only was used in the analysis, tide phase explained 6.7 % of the total variation and 24 % of the variation at the week level (Level 1) ($0.05 < p < 0.10$).

24 h variation

Large catches of juvenile *Penaeus merguiensis* were often restricted to short periods of the day or night (Fig. 4). Tide type, tide stage and the day-night cycle all had some influence on catches. On spring tides the catch of juveniles peaked mainly during the major tide, usually just before or around the time of low tide, during the day or night. Prawns were never caught in daylight on the minor tide.

On neap tides, where the tidal ranges for the major and minor tides are similar, the day-night cycle usually appeared to be more important than the tide type. For example, on 20-21 May, the peak catch during the minor tide at night was almost as high as the peak catch during the major tide by day. Tide type was highly significant, explaining 3.5 % of the total catch variation and 34.5 % of the variation at the day level (Table 2, Level 2). There was also a significant interaction between day-night and the unimodal season variable. This is partly because the largest catches, associated with the major tide, occurred at night for part of the high catch period (December to March) and mainly during the day for the latter part of the year (March onwards). To eliminate the effects of this interaction, mean catches for each combination of tide type, tide phase and day-night were calculated for a period of the year when juvenile *Penaeus merguiensis* were abundant (January to April) and when the major tide occurred at night as well as in the day (Fig. 5). Even with this restricted data set, catches were greater at night and on the major tide, although the difference was more pronounced on spring tides (Fig. 5).

Several interactions involving tide stage were significant in the analysis (Table 2, Level 3). The interaction between tide height and tide stage was highly significant and occurred because catches tended to drop off sharply after low tide. For a given tide height, catches are greater on the ebb tide than on the flood tide. There are also significant interactions between tide stage and season; although the overall pattern is similar, there are subtle changes in the distribution of catches between tide stages at different times of the year. From September to February the major tide was mostly at night and catches of prawns were widely spread throughout the ebb tide cycle when it occurred at night (Fig. 4). From March to July the major tide was mostly during the day and peak catches on this tide were in a short period from the last third of the ebb tide to low tide (Fig. 4).

Analyses of *Penaeus merguiensis* postlarvae data gave similar results, although tide type and stage were less important and day-night was slightly more important. Unlike the juveniles, tide type was not significant in the analysis. Tide stage, however, explained 10.8 % of the total catch variation ($p < 0.001$), tide height added 2.4 % ($p < 0.001$) and day-night added 2.6 % ($p < 0.001$) to the total catch variation explained.

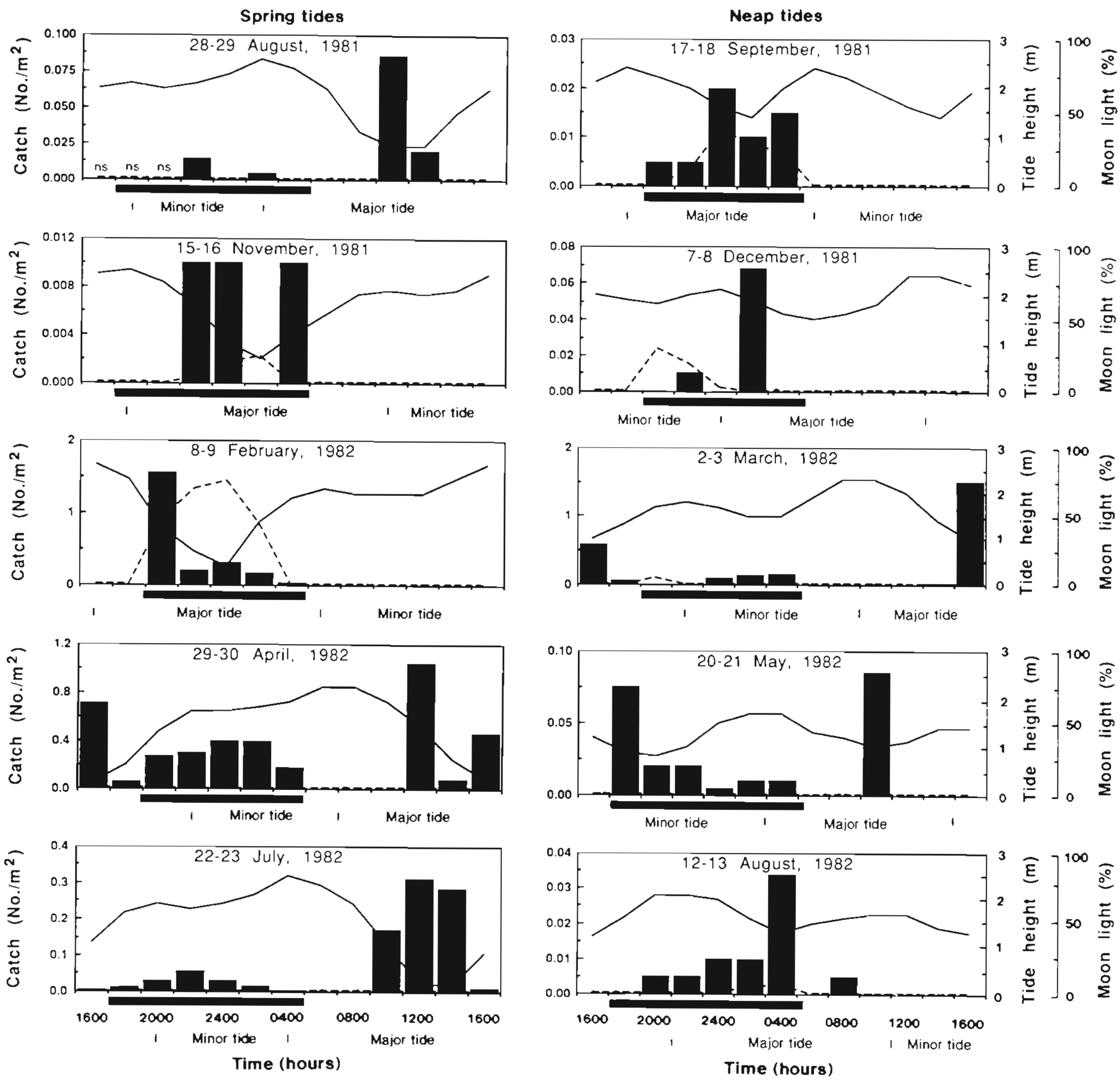

Fig. 4. Juvenile *Penaeus merguiensis*. Catch rates of every second spring and neap tide sampled throughout the year. Catches (histogram), tide height (solid line) and moonlight (dashed line) are presented over 24 h periods. Horizontal bars: hours of darkness; ns: no sample taken

Penaeus esculentus

Seasonal variation

Catches of *Penaeus esculentus* showed 2 distinct seasonal peaks, with the second much larger than the first (Fig. 6). Catches from August to November were moderate, decreased in December and remained low until April. Catches then increased and reached a peak in May. Seasonal effects were therefore fitted as a combination of unimodal and bimodal sine curves, and were highly significant in the analysis of variance (Table 3, Level 1) and explained 46.7 % of the total catch variation and 83.3 % of the variation at the weeks level. There was no apparent effect of tide phase (spring-neap cycle) or moon phase at this level of analysis.

24 h variation

Catches of juvenile *Penaeus esculentus* were variable throughout the 24 h period but, overall, more

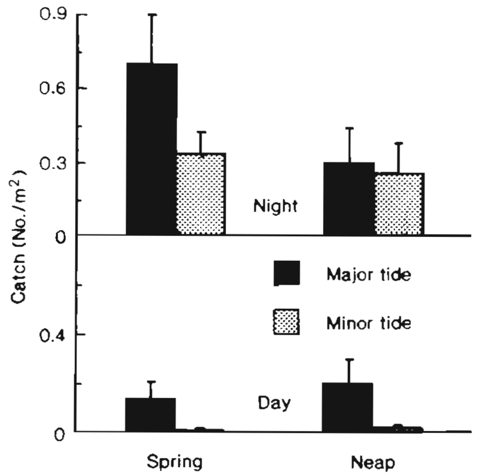

Fig. 5. Juvenile *Penaeus merguiensis*. Mean catches + SE for each combination of tide range, tide phase and day-night for the period January to April

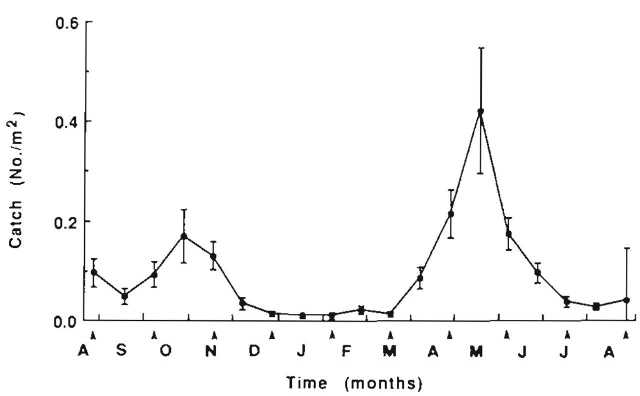

Fig. 6. Juvenile *Penaeus esculentus*. Mean catches ± SE for each sampling period from August 1981 to August 1982. Arrowheads: dates of alternate spring tides. n = 13 for each point

prawns were caught at night (Fig. 7). Day-night was highly significant and explained 3.6 % of the total catch variation, but 44.2 % of the variation at the day level (Table 3, Level 2). The significant interactions between day-night and season and between tide stage and season (Table 3, Level 3) are probably due to seasonal changes in abundance; although more prawns were caught at night and peak catches tended to occur on the low tide stages (Fig. 7), these patterns obviously did not occur when seasonal abundances were virtually zero.

Metapenaeus endeavouri

Seasonal variation

Catches of juvenile *Metapenaeus endeavouri* showed 2 distinct seasonal peaks. Catches were highest from November to mid-January, declined sharply in February and increased again in May, reaching a second peak late in June (Fig. 8). The bimodal season variable was highly significant, explaining 9.5 % of the total catch variation and 70 % of the variation at the weeks level (Table 4, Level 1). There was no apparent relationship between catches and tide phase or moon phase.

24 h variation

Catches of *Metapenaeus endeavouri* were clearly affected by the day-night cycle (Fig. 9): virtually no prawns were caught during the day, but catches were variable throughout the night period. There was an interaction between day-night and the bimodal season

Table 3. *Penaeus esculentus*. Split-plot analysis of variance of log-transformed catches of juveniles with season, tide stage, and day-night. Level 1 tests variability between weeks, Level 2 between tide types and Level 3 between tide stages. Definitions as in Table 2. Only significant effects are included in the model

Split plot	Source of variation	df	SS	*F*-ratio	% Level variation	% Total variation
Level 1 (Weeks)	Bimodal season	2	2.572	18.64***	44.4	24.9
	Unimodal season	2	2.253	16.33***	38.9	21.8
	Error	14	0.972			
Level 2 (Day)	Day-night	1	0.376	14.27***	44.2	3.6
	Error	18	0.474			
Level 3 (Hours)	Day-night	1	0.519	38.16***	17.1	5.0
	Tide-stage	7	0.235	2.46*	7.7	2.3
	Day-night × Bimodal season	2	0.215	7.71***	7.1	2.1
	Tide stage × Bimodal season	14	0.463	2.36**	15.2	4.5
	Error	118	1.605			

*0.01 < p < 0.05, **0.001 < p < 0.01, ***p < 0.001

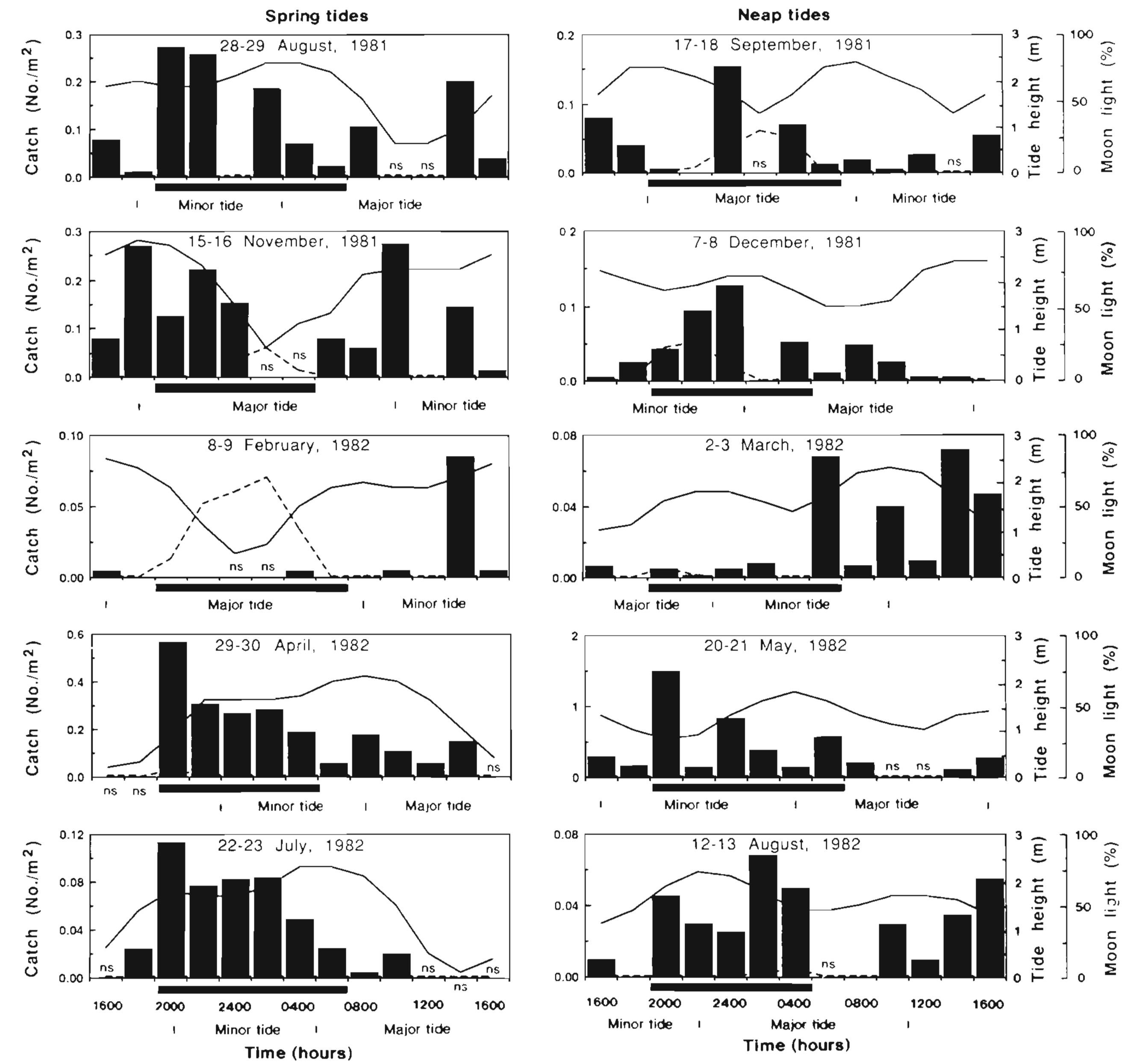

Fig. 7. Juvenile *Penaeus esculentus*. Catch rates of every second spring and neap tide sampled throughout the year. Catches (histogram), tide height (solid line) and moonlight (dashed line) are presented over 24 h periods. Horizontal bars: hours of darkness; ns: no sample taken

variable (Table 4, Level 2) because of seasonal abundance changes: whenever prawns were abundant they were virtually all caught at night, but on several occasions during the year almost no prawns were caught and therefore no day-night pattern of catches could be detected.

There was a significant interaction between day-night and tide stage (Table 4, Level 3) because catches occurred across tide stages only at night. The interaction between day-night and season (Table 4, Level 3) is due, as at Level 2, to seasonal changes in the abundance of prawns. Peak catches tended to occur near low tide (Fig. 9), but when prawn abundances were very low this pattern was not clearly seen.

DISCUSSION

To plan a strategy for sampling juvenile prawns, it is essential to be able to distinguish real long-term changes in abundance in the area of interest from apparent changes due to either long-term or short-term

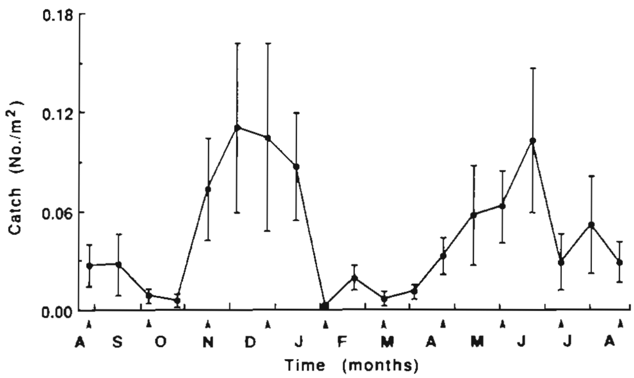

Fig. 8. Juvenile *Metapenaeus endeavouri*. Mean catches ± SE for each sampling period from August 1981 to August 1982. Arrowheads: dates of alternate spring tides. n = 13 for each point

changes in catchability on the site chosen to represent the larger area. This is not always easy. Long-term changes in abundance are determined by large-scale migrations to or from the nursery grounds or by mortality in the sampling area. Short-term variations in catches may be caused by either regular small-scale movements of prawns on and off the sampling site or by changes in their catchability on the sampling site. Catchability depends on the availability of the prawns (i.e. whether buried or not buried, active or not active) and their response to the sampling gear.

24 h variation

In the present study, the main factors affecting catchability over a 24 h period were changes in the day-night and tidal cycles. All species showed a similar response to the day-night cycle, but the strength of the effect varied from juvenile *Metapenaeus endeavouri*, which were caught only at night, to juvenile *Penaeus merguiensis*, where tide had an overriding effect. This gradient of response is largely a reflection of the behaviour of each species at different levels of activity. Laboratory studies have shown that these 3 species are all more active at night (Vance 1992) (Fig. 10a): *M. endeavouri* is most sensitive to day-night changes and remains buried throughout the day, while *P. esculentus* and *P. merguiensis* are active during the day but most active at night (Fig. 10a). *P. esculentus* is often buried or partially buried during the day, whereas *P. merguiensis* was never seen to bury under laboratory conditions. The decreased catchability of *M. endeavouri*, and to a lesser extent *P. esculentus*, during the day was therefore because these species were buried and unavailable for capture by the beam trawl (Fig. 10b). The decreased catchability of *P. merguiensis* during the day may be because the prawns are better able to see and avoid the trawl.

Other studies have also shown that many penaeids are more catchable at night, including juvenile *Penaeus plebejus* (Coles 1979), juvenile and adolescent *P. duorarum* (Eldred et al. 1961) and adult *P. esculentus* (White 1975). Laboratory studies have also shown these species to be night-active (e.g. adult *P. plebejus*, Racek 1959; adult *P. esculentus*, Hill 1985; juvenile *P. duorarum*, Reynolds & Casterlin 1979). Other species of the white prawn group such as *P. setiferus* can be caught during both day and night, although laboratory studies have shown that, like *P. merguiensis*, these prawns are more active during the night (Wickham & Minkler 1975).

In this study, catches of the 3 species varied in a similar way with respect to tide. After day-night effects

Table 4. *Metapenaeus endeavouri*. Split-plot analysis of variance of log-transformed catches of juveniles with season, tide stage, and day-night. Level 1 tests variability between weeks, Level 2 between tide types and Level 3 between tide stages. Definitions as in Table 2. Only significant effects are included in the model

Split plot	Source of variation	df	SS	*F*-ratio	% Level variation	% Total variation
Level 1	Bimodal season	2	0.767	18.29**	70.0	9.5
(Weeks)	Error	16	0.329			
Level 2	Day-night	1	1.020	37.44***	58.1	12.4
(Day)	Day-night × Bimodal season	2	0.301	5.59*	17.2	3.7
	Error	16	0.436			
Level 3	Day-night	1	2.615	221.43***	49.3	32.5
(Hours)	Tide-stage	7	0.284	3.44**	5.4	3.5
	Day-night × Tide stage	7	0.312	3.77***	5.9	3.9
	Day-night × Bimodal season	2	0.616	25.67***	11.6	7.7
	Error	125				

*0.01 < p < 0.05, **0.001 < p < 0.01, ***p < 0.001

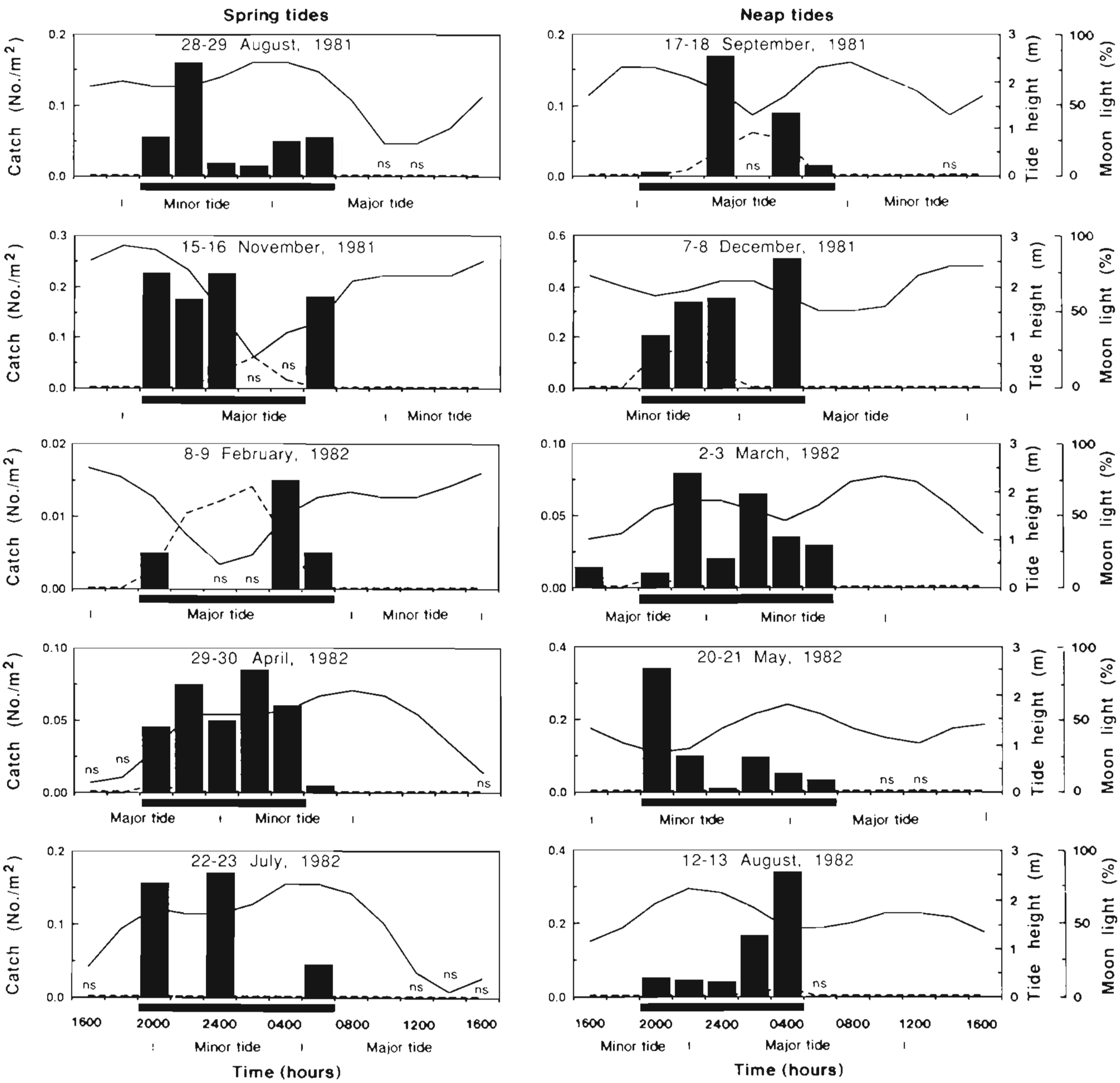

Fig. 9. Juvenile *Metapenaeus endeavouri*. Catch rates of every second spring and neap tide sampled throughout the year. Catches (histogram), tide height (solid line) and moonlight (dashed line) are presented over 24 h periods. Horizontal bars: hours of darkness; ns: no sample taken

were removed, catches of all species were lowest at high tide. *Penaeus merguiensis* catches were highest just before and around low tide, while *P. esculentus* and *Metapenaeus endeavouri* catches were highest just before and after low tide (Fig. 10d). Vance (1992) also found that these 3 species were more active at high tide than low tide (Fig. 10c). This suggests that the 3 species tend to be more catchable when they are least active, although their catchability may be further modified by burying behaviour or by abundance changes on the sampling site. The decreased catches of juvenile *P. merguiensis* at high tide were at least partly due to the prawns being inside the mangrove forest and therefore inaccessible to the trawl (Vance et al. 1990). Vance et al. (1990) suggested that juvenile *P. merguiensis* migrate between small creeks and the main river following the water level on each daily tidal cycle. They become concentrated close to the water's edge in the main river at low tide and remain relatively inactive, possibly using the turbid water as protection

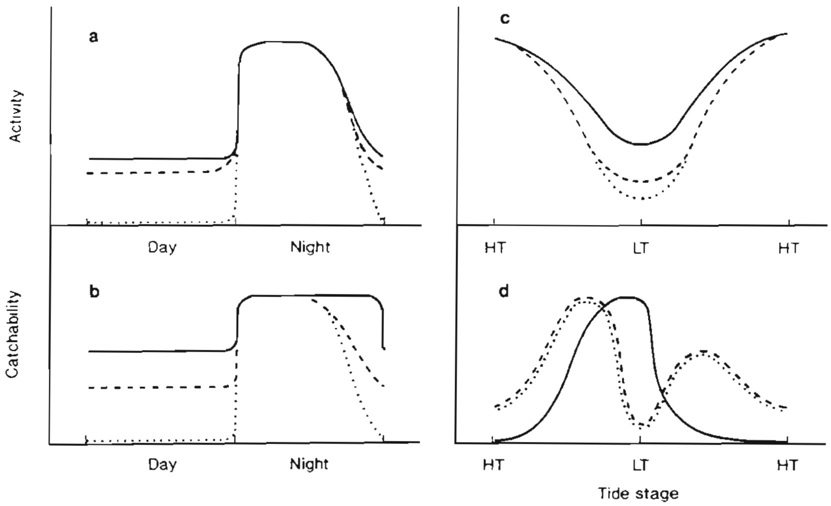

Fig. 10. Summarised cycles of (a) activity and (b) catchability throughout 1 day-night cycle and (c) activity and (d) catchability throughout 1 tidal cycle. HT: high tide; LT: low tide; (——) *Penaeus merguiensis*; (-----) *Penaeus esculentus*; (·····) *Metapenaeus endeavouri*. Summarised activity curves are drawn from Vance (1992)

from predators. However, they become more catchable to the trawl at this time (Fig. 10d).

On *Penaeus esculentus* and *Metapenaeus endeavouri* habitat, the trawl net covered less than 100 % of the vertical water column at high tide and some prawns may have been swimming above the path of the net. *P. esculentus* and *M. endeavouri* became more catchable as the tide height decreased and the height of the water column became closer to that of the trawl net. In contrast to *P. merguiensis*, however, at low tide, these prawns were least catchable to the trawl. This suggests that the number of prawns becoming inactive increased towards low tide until many had buried and were thus unable to be caught (Fig. 10d). The seagrass habitat is often exposed on spring low tides, at which time these species remain buried amongst the seagrass (Vance, CSIRO Division of Fisheries, unpubl. data).

Like the 3 species of penaeids in this study, *Nephrops norvegicus* have been shown, under some circumstances, to be least catchable when they are most active. Laboratory experiments have shown increased activity during the hours of darkness whereas most catches are made during the day. However, the increased activity seems to occur within burrows, which presumably makes *N. norvegicus* unavailable for capture by trawls at this time (Atkinson & Naylor 1976).

Interestingly, for the 3 penaeid prawns described in this paper, the relationship between activity and catchability was different for the day-night and tidal cycle. Catchability with respect to the day-night cycle increased when the prawns were more active but the catchability with respect to the tidal cycle increased when the prawns were less active. Each of these relationships is understandable, as explained in the previous paragraphs, but the interaction between them makes the catchability patterns observed in the field quite complicated.

Spring-neap tide variation

Penaeus merguiensis was the only species for which catches appeared to be affected by the fortnightly spring-neap cycle: larger catches were taken on the spring tides. This variation in catches is due to changes in abundance of prawns on the sampling site, caused by small-scale movements of prawns onto and off the site. The mangrove-lined mud bank habitat favoured by *P. merguiensis* is widespread and extends up small side creeks. On neap low tides water usually remains in the small creeks, but on spring low tides many of the small creeks and channels drain dry and prawns move out into the larger creeks and rivers (Robertson 1988). On spring low tides, much less habitat would be available in the small creeks than on neap low tides, so the number of juveniles moving out of the small creeks near low tide would therefore be greater. Because the *P. merguiensis* sampling site was in the main river, catches on spring low tides were probably increased by the greater numbers of prawns moving out of the small creeks. On neap tides, more prawns remained in the small creeks and catches in the main river were lower. The juveniles of *P. esculentus* and *Metapenaeus endeavouri*, however, are much less mobile within the estuary: they remain on the seagrass areas at low tide and are therefore less affected by spring-neap tide changes.

Seasonal variation

At the seasonal level, catch variation was probably due to real changes in abundance in the estuary. However, in some regions, catchability may be influenced by seasonal variations in temperature, which must be taken into account when assessing seasonal variation in catches. White (1975) suggested that seasonal changes in catch per unit effort of adult *Penaeus esculentus* in Exmouth Gulf, Western Australia, may be due to changes in water temperature. Hill (1985) found that the time adult *P. esculentus* spent buried in the laboratory at night was directly related to water temperature: it ranged from less than 1 h emerged from the substrate at 16 °C to greater than 6 h at 24 to 26 °C. In the present study the minimum water temperature recorded at the Embley River was 22°C. Temperature was not significant in the analyses of variances for any of the 3 species and is unlikely to have had a marked effect on their catchability. Cycles of abundances agreed well with published accounts of seasonal cycles of other life-history stages of *P. merguiensis* (Rothlisberg et al. 1985) and *P. esculentus* (Crocos 1987, Somers et al. 1987).

Sampling strategies

Catches of juvenile *Penaeus merguiensis*, *P. esculentus* and *Metapenaeus endeavouri* in the Embley River varied markedly both seasonally and within 24 h sampling periods, and the causes of variation differed depending on the time scales. Long-term seasonal and spring-neap tide phase changes were due mainly to changes in abundance in the estuary or on the sampling site. Short-term changes in catch of *P. esculentus* and *M. endeavouri* over a 24 h period were due to catchability changes of the prawns on the sampling sites. *P. merguiensis* was much more mobile within the estuary, and short-term fluctuations in catches of this species were also influenced by abundance changes on the sampling site.

To compare the abundances of juvenile prawns over months or years, each sample must be taken at a similar stage of the catchability cycle, and preferably when the catches peak for each species. The results of this study suggest that this can be done for juveniles of *Penaeus merguiensis*, *P. esculentus* and *Metapenaeus endeavouri* as long as a consistent stage of the day-night and tidal cycle is sampled. The highest catches of all species would be taken during the period when the first 2 or 3 h of darkness coincided with the last 2 or 3 h of the ebb tide. However, this combination of conditions does not often occur so regular sampling cannot be based solely on this timing.

In general, trawl sampling for juvenile *Penaeus merguiensis* should be carried out during the last 2 or 3 h of the ebb tide, after the water level has dropped below the mangrove line, and irrespective of the day-night cycle (Table 5). During this period, juvenile *P. merguiensis* become concentrated in the main creeks and rivers as the water level drops in the small gutters and creeks. Trawls, therefore, should be made at a fixed tide height, so that this concentrating effect is comparable between sampling periods. If tides are semi-diurnal, then the ebb tide with the largest range should be sampled. Catches may be expected to be higher if the low tide is at night rather than the day.

Table 5. Optimum stages of the tidal and day-night cycles for trawl sampling of *Penaeus merguiensis*, *P. esculentus* and *Metapenaeus endeavouri* to provide reliable long-term comparisons of abundance

Species	Tidal cycle	Day-night cycle
P. merguiensis	Last third of ebb tide	Day or night
P. esculentus	First third of flood tide	Night
M. endeavouri	First third of flood tide	Night

Sampling for *Penaeus esculentus* and *Metapenaeus endeavouri* should be carried out at night (Table 5). Although maximum catches could be expected at about two-thirds of the ebb tide, there are practical difficulties in sampling intertidal seagrass beds at late stages of the ebb tide. This stage of the tide cycle is, therefore, not useful for reliable long-term sampling. Regular sampling should be carried out on the first third of the flood tide when the seagrass beds are accessible. As for *P. merguiensis*, sampling should be carried out at a fixed tide height to minimise catch variation caused by differences in the volume of water available for occupation by the prawns.

Several conflicting factors must be balanced when determining the optimum frequency of sampling for each species. Sampling at monthly intervals would enable samples to be taken at the same stage of the tidal and moon cycle; catches of *Penaeus merguiensis* were certainly influenced by the timing of the spring-neap tidal cycle, but this variation can probably be eliminated by sampling at a constant tide height. Catches of all 3 species are probably affected by extreme changes in moon phase. Fuss & Ogren (1966) found that moonlight inhibited the emergence of adult *P. duorarum*. In the intertidal areas less than 4 m deep inhabited by juvenile *P. merguiensis*, *P. esculentus* and *Metapenaeus endeavouri*, moonlight is probably also important. These effects are difficult to detect, although there is some evidence in the present study that moonlight sometimes had an inhibitory effect [e.g. 8–9 February (Figs. 4, 7 & 9)]. In any case, monthly sampling may not provide sufficient data for long-term comparisons, because the main juvenile production that contributes to the offshore fishery for *P. merguiensis* at Weipa only occurs over about 4 mo each year, and most juveniles spend less than 4 mo in the nursery areas (Rothlisberg et al. 1985; M. D. E. Haywood & D. J. Staples, CSIRO Division of Fisheries, unpubl. data). It is preferable to sample at least fortnightly to adequately compare abundances of postlarvae and small juvenile prawns. Sampling should be carried out between the extremes of full and new moon, but allowances may still have to be made for the intensity of moonlight at the time of sampling.

Recent sampling at Weipa has shown that juvenile *Penaeus merguiensis* were up to 5 times more abundant in a small creek than in the main river, and the size composition of the populations at each location was also different (Vance et al. 1990). Therefore *P. merguiensis*, and other highly mobile species, should be sampled at several different locations in the estuary to accurately estimate overall abundance.

The conclusions reached in this study should be relevant to sampling for many juvenile penaeids throughout the Indo-West Pacific region. *Penaeus merguiensis* occurs from the Persian Gulf to eastern Australia. *P. esculentus* is endemic to Australia but *P. semisulcatus*, which utilizes the same estuarine habitat as a juvenile, is caught commercially from eastern Africa to eastern Australia. Catchability patterns of *P. semisulcatus* at Weipa are very similar to those of *P. esculentus* (Vance, CSIRO Division of Fisheries, unpubl. data).

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